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TWO-PHASE CONVECTION IN IGNEOUS MAGMAS[1]

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A careful study of the Duluth gabbro led the writer to the idea of a convection circulation in the magma. A review of the literature shows nothing conclusively opposed to the idea, though the structures are explained in many other ways. This paper summarizes the signs of convection and suggests its probable mechanism and results.

SIGNS OF CONVECTION IN MAGMAS

1. The fluxion structure of many rocks is a strong indication that movement occurred during crystallization. When combined with an alternation of differentiated bands and a roughly gravitative arrangement of the bands, the only explanation that is at all satisfactory is that the movement is one of circulation rather than of intrusion or of deformation.[2]

2. Convection has been observed directly in lava lakes in the craters of volcanoes. These highly special conditions of magma, however, are not sufficient to convince everyone that convection is a common process in deeper magmas.

[1] Part of a thesis presented to the faculty of Yale University for the degree of Doctor of Philosophy.

[2] Frank F. Grout, "Internal Structures of Igneous Rocks," etc., *Jour. Geol.*, XXVI, No. 5 (1918).

3. The texture of an intrusive mass in relation to its borders and its contact metamorphism may be a sign of convection. Lane[1] and Queneau[2] have shown that in the case of simple conduction of heat away from a stationary mass the grain of the rock will not be uniform up to the contact unless the magma temperature was farther above the temperature of crystallization than the wall-rock temperature was below. As Lane puts it, measured from the temperature of the surrounding rock as zero, the magma must be more than twice the temperature of solidification. For an intrusion at moderate depths into cold rocks, this means more superheat than is commonly supposed to exist. The observed superheat is seldom over 200° to 300°C.

4. The arrangement of the extreme differentiates in a laccolith might be a strong indication of convection. If the outer layer is of average composition it may be attributed to chilling, but if a layer found on all sides, top and bottom, is an extreme of the series of differentiates it can be attributed to neither chilling nor gravity. An illustration is found in the Lugar sill in Scotland.[3] The average material of the sill has scarcely 20 per cent of salic constituents, but the border phases have over 40 per cent of feldspar and feldspathoid material. Since diffusion is shown to be too slow a process,[4] the only way to get the extreme product segregated to all sides is by a circulation of some sort.

5. A differentiated dike found by the writer at Duluth is very suggestive. The dike is four feet wide and is pegmatitic in nature a few feet below the base of the main gabbro. Its texture is particularly coarse at the sides, where the composition is that of a gabbro, and it is evident that the crystals must have grown large by additions from the residual circulating or passing magma in the center of the dike. From these coarse gabbro borders there is a complete gradation to a medium-grained red granite in the center of the dike.

[1] A. C. Lane, "The Grain of Rocks," *Bull. Geol. Soc. Am.*, VIII, 403.

[2] A. L. Queneau, *School of Mines Quarterly*, XXIII (1902), 181.

[3] G. W. Tyrrell, "Alkaline Igneous Rocks of West Scotland," *Geol. Mag.*, IX (1912), 75–77.

[4] N. L. Bowen, "Later Stages of Evolution of Igneous Rocks," *Jour. Geol.*, Supplement, December, 1915, p. 12.

There is no sign whatever of an internal contact between the two rocks such as would indicate successive intrusions. Neither is there any fluxion structure such as a strong extrusive movement during crystallization would be expected to produce. It is much more likely that the gabbro and granite separated from the same liquid, and that this was moved about only slightly, by convection or by a late phase of injection, so that the supply of basic minerals to the sides was continuous until all had crystallized.

THE MECHANICS OF CONVECTION IN IGNEOUS MAGMAS

The nature of convection.—The familiar illustration of convection is the local heating of a tank of water, with some suspended matter to make its motion visible. The density in different parts of the tank is different enough to start a motion of readjustment, and if the difference is maintained by a continuous heat supply and continuous cooling elsewhere, a circulation is maintained. As applied to magmas the process was suggested by Becker and has been widely applied.[1] The chief factors which control the rate of circulation are the differences in density in different parts of the container and the viscosity of the liquid; and both of these factors vary with temperature. Water, which is the liquid in most laboratory experiments, shows a very great density change with temperature, and its viscosity is very low as compared with that of igneous magma. Both conditions being exceptionally favorable, it is clear that the illustration should not be applied to magmas without some estimate of its quantitative importance.

Two-phase convection.—Besides the well-known changes in density in a magma from changes of temperature, there are other density effects due to a separation of phases. The separation of gases and crystals from lava is a matter of common observation. The separation of gases was suggested by Pirsson[2] as a possible means of deep-seated stirring, and the idea was further developed by

[1] G. F. Becker, "Some Queries on Rock Differentiation," *Am. Jour. Science*, III (1897), 21. L. V. Pirsson, "The Igneous Rocks of the Highwood Mountains," *U.S. Geol. Surv. Bull. 237*, pp. 184 and 189.

[2] L. V. Pirsson, "The Petrographic Province of Central Montana," *Am. Jour. Sci.*, XX (1905), 47.

Daly[1] in explaining the supply of heat from depth to lava lakes—he called it two-phase convection.

It seems perfectly clear, from a general consideration of the idea, that a mass of lava filled with bubbles would have a lower "aggregate specific gravity" than a neighboring mass without such bubbles. Any process of local vesiculation would almost certainly result in convection. It is perhaps less clear and less often emphasized, but none the less true, that a mass of lava in which crystals have formed has a greater "aggregate specific gravity" than it had just before, and a local development of crystals would also almost certainly start convection. In the case of gas bubbles in a magma the escape of the gas from a crater lake would finally remove the cause of the circulation. In order to maintain the circulation there must be a continuous supply of gas bubbles to some portion of the magma. Similarly, if crystals settle out of a liquid magma they would no longer tend to move the liquid. The circulation caused by the density of crystals would be active only during the time in which crystals were developing locally in the liquid and settling through it. However, in a large body of magma either of these processes might be maintained for a long time.

THE DEVELOPMENT OF PHASES IN MAGMAS

Phases are defined in physical chemistry as the parts of a system which are mechanically separable. A simple magma consists of one liquid phase. Considered as a solution, the magma may contain various dissolved substances, including many minerals as well as gases and water; but it remains one phase and only one.

Gas phase.—When bubbles of gas separate from solution in a magma and remain in it as parts of a closed system (i.e., do not mingle with the outside air), they may be considered a second phase in the magma. The conditions and reasons for their separation are various. The solubility of gas in a liquid varies with the pressure. If a magma saturated with gas at a pressure of 200 atmospheres is erupted to the surface, where the pressure is one atmosphere, gas will separate from the solution. It is equally sure

[1] R. A. Daly, "The Nature of Volcanic Action," *Proc. Am. Acad. of Arts and Sci.*, XLVII, 76.

to separate if intruded in a region of less pressure, even if it does not reach the surface. The solubility of a gas also varies with the temperature and with certain changes in the composition of the magma. For example, the assimilation of other rocks or liquids may so change the composition as to make the gas less soluble. It becomes evident that gases may separate at considerable depth as well as at the surface.

Crystal phase.—It is a commonplace that a magma on cooling and under various modifying influences will crystallize in a series of mineral compounds. In the closed system, with some of the mother-liquor, each constitutes a phase.

New liquid phases.—The question of immiscibility in magmas may be left open. While it is not well to use the term as if the process were known, the discussion of probable cases would not be complete without the consideration of new liquid phases. Changes in temperature or composition are the explanations given for their separation.

FACTORS IN MAGMA MOVEMENTS

The points to consider in a discussion of convection are the forces applied and the viscosity and related effects tending to oppose or retard movement. We are not now concerned with the forces leading to the intrusion of magmas. The estimate of forces is wholly dependent on specific gravities and on the volume of the portions of different specific gravities. These must be estimated. The viscosity of magmas is known to be variable with composition, pressure, and temperature; and in the present case we must estimate the added effect of the presence of a second phase.

Viscosity.—The factor of viscosity is so great that by many the possibility of active convection in a crystallizing magma is dismissed as an absurdity; but the field evidence is strong enough to warrant a quantitative estimate. Furthermore there may be in the minds of many a misconception of the true nature of increased viscosity. A truly viscous fluid, as distinct from a weak solid, will yield to any small force if given time. Viscosity cannot inhibit the movement, but can only retard it. In a pitch a million of million times as viscous as water, stones will sink and cork will rise in a few weeks.

On the other hand, in as weak a solid as gelatine gas bubbles and small solids remain stationary indefinitely. Bowen's work on the settling of crystals[1] may be taken as evidence that a magma during crystallization is truly viscous. In such a liquid, then, any appreciable force applied is entirely sufficient to start action. It simply remains to estimate possible counteracting forces and the rate of motion likely to result.

It was estimated by Becker[2] that Hawaiian lavas were about fifty times as viscous as water (0.575 in C.G.S. units; water at 15°, 0.0115). Daly[3] estimates that rhyolites may be erupted at a viscosity of 11.5. Ranging from these values for actively moving magmas, we may be sure that on cooling the viscosity increases until in glasses it is almost infinite. Data connecting the viscosity with temperature are not available. Fortunately Bowen has noted the rate of settling of certain crystals and thus obtained some very useful estimates for viscosity *during crystallization*,[4] which is the condition of most importance rather than the actual temperature. His figures for probable maximum viscosities are 4 to 200 in C.G.S. units for melts ranging from basic to acid character, in which crystals are growing. Bowen calls these figures maxima because of the probable growth of the crystals during settling. Several factors tend to reduce the values in nature. The extreme fluidity actually shown[5] by intrusive magmas may be due to their retention of more water vapor than is the case in extrusive lavas. In agreement with this are the results of Morey[6] showing that fusions in the presence of steam show a remarkable decrease in viscosity. The importance of water in magmas is attested by hydrous minerals and miarolitic cavities in the rocks. On the other hand, some conditions may increase viscosity. Doelter found that pressure increased it, but

[1] N. L. Bowen, "Crystallization Differentiation in Silicate Melts," *Am. Jour. Sci.*, XXXIX (1915), 186.

[2] G. F. Becker, *op. cit.*, p. 29.

[3] R. A. Daly, "Mechanics of Igneous Intrusion," *Amer. Jour. Sci.*, XXVI (1908), 30.

[4] N. L. Bowen, "Crystallization Differentiation in Silicate Melts," *Am. Jour. Sci.*, XXXIX (1915), 186.

[5] A. Harker, *The Natural History of Igneous Rocks*, p. 223.

[6] G. W. Morey, "New Crystalline Silicates of Sodium and Potassium," *Jour. Amer. Chem. Soc.*, XXXVI (1914), 226.

added that 10,000 meters of rock would probably increase it no more than 30 per cent.[1] This estimate, like the others, may be modified 100 per cent or more by careful work, but may be taken as of the approximate order of magnitude. Applying this addition to Bowen's figures, we have as probable maximum viscosities in even figures 5 to 300 in C.G.S. units.

The effect of new phases remains to be considered. It may be assumed that moderate amounts of a gas or liquid phase will have little effect on the motion of bodies of magma. The accumulation of crystal phases, however, may give a decided difference in results. Direct data not being available, it is well to consider analogous cases. Curves have been drawn showing the effect of clay added to water and dilute water solutions. Though the increase in viscosity may be great in some cases, it is shown that a slip with 50 per cent solids may have a viscosity less than 10 per cent greater than that of water.[2] A rough test by the writer, with starch and rock powders of about 80 mesh, up to 25 per cent of volume, showed an increased bulk viscosity of less than 5 per cent. This would have little effect on the maxima above estimated. Bowen estimates that a magma may be eruptible even with 50 per cent crystals.[3] The maximum viscosities assumed in this paper will therefore be from 5 to 300.

The thermal gradient in magmas.—The variations in temperature in different parts of a magma during the cooling process have not often been estimated. Estimates of the thermal gradient in a magma occupying a chamber may be made from the calculations and assumptions of several authors, but they vary from 100° to 300° C.[4] Since it is here argued that convection would occur, let us assume that cooling occurs without convection, and calculate the forces tending to start such convection. For example, assume

[1] C. Doelter, *Physikalisch-chemische Mineralogie* (1905), p. 110.

[2] A. V. Bleininger; *U. S. Bureau of Standards Technologic Paper 51* (1915), pp. 25–30.

[3] N. L. Bowen, "Later Stages of Evolution of Igneous Rocks," *Jour. Geol.*, Supplement, December, 1915, p. 31.

[4] R. A. Daly, *Igneous Rocks and Their Origin*, pp. 224 and 258; A. Harker, *op. cit.*, p. 316; A. C. Lane, "Coarseness of Igneous Rocks," *Amer. Geol.*, XXXV (1905), 71; Ingersoll and Zobell, *Mathematical Theory of Heat Conduction*, etc. Ginn & Co., 1913.

that a magma at 1,300°C. may be intruded at a horizon a mile below the surface which may have a temperature not over 100°, average probably 50°. The heat loss can be calculated by the formula

$$Q=\frac{kAt(T-T_1)}{x},$$

where k is the conductivity in C.G.S. units, A the area in square centimeters, and $(T-T_1)$ the difference in temperature. So long as the surface of the earth was kept cool, the upward flow of heat would be fairly uniform until the magma cooled appreciably. On the other hand, the temperature at the floor will not remain uniform. The floor of the Duluth gabbro must have sunk nearly 10 miles. The isogeotherms would rapidly rise. The lava streams that fed the intrusion and even the approach of the magma chamber below would contribute to the rapidity of the rise. With these supplies of heat from below, the heat added to the floor by the gabbro would accumulate rather than pass on. A rough calculation by the same formula indicates that the gabbro added heat to its floor in a year equivalent to a general rise in temperature of 12° for the first mile. In 100 years the floor would be so hot that heat losses in that direction would be very small. The gabbro as a whole, however, would cool only a few degrees in 100 years. Thus it seems that by the time crystallization begins the loss of heat is likely to be from the top and sides of the chamber. If this loss occurred without convection—say from a zone 10 to 15 meters thick at the roof—this zone would be cooled 100° below the main body of the magma very soon, say within a month. In a few years the contrast in temperature would be much greater. It is therefore assumed that a difference in temperature of 100°C. in different parts of a medium to large magma is not unusual.

The specific gravities of phases.—Specific gravity varies with composition, temperature, and crystalline or glassy structure. Daly, in summarizing the results of several investigators, estimates that the change from liquid to crystalline rocks at the same temperature results in an increase of specific gravity as follows: 6 per cent for gabbros and diorites, 7 per cent for quartz-diorite, 8 per cent

for syenite, and 9 per cent for granite.[1] The data need confirmation, as authorities disagreed as much as 100 per cent. The difficulty of accurate estimates has been shown by Day, *et al.*[2] The expansion with temperature is estimated at 0.000025 volume per degree Centigrade, but is greater for liquids than solids.[3] From these one may roughly estimate the proper order of magnitude as given in Table I, though the figures may be far from accurate in detail. Attention is called to the small differences due to temperature alone as compared with larger ones due to a change from liquid to solid and to changes of composition.

TABLE I

APPROXIMATE SPECIFIC GRAVITIES OF PHASES IN MAGMAS

	At 1000°		At 1100°	
	Solid	Liquid	Solid	Liquid
Average Granite	2.63	2.40	2.62+	2.39
Quartz	2.60	2.37	2.59	2.36
Orthoclase	2.49−	2.27	2.48	2.26
Average Gabbro	2.92	2.75	2.91+	2.74
Plagioclase, Ab_6An_1	2.58	2.41	2.57	2.40
Plagioclase, Ab_1An_1	2.62−	2.46	2.61	2.45
Magnetite	5.05	4.80	5.03	4.77
Olivine	3.24	3.05	3.23	3.04
Augite	3.15	2.96	3.14	2.95

ESTIMATING CONVECTION EFFECTS

No formulas seem to have been developed which can be directly applied to the estimation of the rate of convection circulation. Daly uses an ingenious combination of calculations of (1) the rate of movement of small solid or gaseous spheres, (2) the size which is the limit of application of this formula, and (3) the relative rates for larger spheres.[4] The essential differences between such movement of spheres and convection are, first, that the magma moves

[1] R. A. Daly, "Mechanics of Igneous Intrusion," *Am. Jour. Sci.*, XXVI (1908), 27.

[2] A. L. Day, *et al.*, "Determination of Mineral and Rock Densities at High Temperatures," *Am. Jour. Sci.*, XXXVII (1914), 1.

[3] C. Barus, "High Temperature Work in Igneous Fusion," *U. S. Geol. Surv. Bull. 103*.

[4] R. A. Daly, *Igneous Rocks and Their Origin*, pp. 260–64.

as a larger mass than any sphere considered; and secondly, that the moving mass is not impeded by a liquid of uniform character, but on one side has a more viscous wall, while on the other side there is less resistance and some added tendency to move. On the whole, however, such a calculation may give a fair idea of the order of magnitude of the motion.

The rate of flow of liquids through a pipe may be compared with the rate estimated by this method. In comparison with the pipe, actual convection, though moving a larger volume of liquid, has the friction of only one solid wall. The evident error of estimating by settling spheres alone appears from the fact that a sphere of 10 meters radius gives the same rate in viscous as in less viscous magma. On the other hand, the formula for flow in a pipe gives too much weight to the matter of viscosity. The best idea is probably obtained from a consideration of both calculations and a comparison with the observed rate of convection in lava lakes.

Thermal convection.—On the basis of the data discussed above we may calculate the rate of settling of large spheres by reason of their greater density when cool.

Assumed temperature difference, 100°C.
Main magma specific gravity, 2.70
Cool magma specific gravity, 2.71
Density difference, .01
Final rate of motion of a sphere of 10 meters radius, nearly 1,000 meters per hour[1]

[1] The calculation for this rate of motion is given in detail for this case. Later estimates are made by the same method. If a small sphere sinks in a viscous liquid the final rate of motion is found by a formula of Stokes in *Trans. of the Cambridge Phil. Soc.*, IX, No. 2 (1850), p. 8.

$$x=\frac{2gR^2(d-d_1)}{9V},$$

where R is the radius of the sphere, d_1 the density of the liquid around it, g the acceleration of gravity, and V the viscosity. The largest sphere that will obey this law is calculated by a formula given by Allen in *Phil. Mag.*, L (1900), 324:

$$R^3=\frac{9V^2}{2gd(d-d_1)}.$$

For larger spheres the velocities are proportional to the square roots of the radii

$$\frac{x'}{x''}=\frac{\sqrt{R'}}{\sqrt{R''}}.$$

In the case of thermal convection, the second formula becomes

$$R^3=\frac{9(5)^2}{2(980)(2.70)(.01)}=4.2,$$

Gas-phase convection.—This case is covered by Daly.[1] He assumes from observations on vesicular lava at craters 200 "standard" (1 mm. at surface pressure) bubbles per cubic centimeter. At a depth of 3,000 feet a magma is under a pressure of 200 pounds per square inch. This is a greater pressure than some magmas are subjected to, but it is to be noted that the gas is not only compressed, but more soluble under pressure—a fact which Daly does not seem to consider. There should also be mentioned some thermal effects connected with the separation, reaction, and expansion of the gas bubbles; but too little is known of the effect of these factors on the density to include them in the calculation.

To obtain data comparable with those of other calculations in this paper the following case was selected:

Assumed pressure, 200 pounds per square inch
Assumed vesiculation, 200 "standard" bubbles per cubic centimeter
Magma specific gravity, 2.70
Vesiculated magma specific gravity, 2.638
Density difference, .062
Final rate of motion of a sphere of 10 meters radius, over 2,200 meters per hour.

Double liquid-phase convection.—If an intermediate magma splits into two immiscible liquids, consisting of granite and gabbro phases, the difference in specific gravity might be so great that a rapid separation of the two would occur; but it is not certain that the separation of immiscible globules is accompanied by any pronounced change in the aggregate specific gravity.

Crystal-phase convection.—The effects of the development of crystals should be emphasized, because of the certainty of the

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when the viscosity is 5. From this, $R = 1.6$ cm. When R is 1.6 cm. and $V = 5$, the Stokes formula becomes

$$x = \frac{2(980)(1.6)^2(.01)}{45} = 1.1 \text{ cm.}$$

per second. For a sphere of 10 meters radius, the last formula

$$\frac{x'}{x''} = \frac{\sqrt{R'}}{\sqrt{R''}} \quad \text{becomes} \quad \frac{1.1}{x''} = \frac{\sqrt{1.6}}{\sqrt{1000}}.$$

From this $x'' = 27$ cm. per second. This is 972 meters per hour.

For the greater viscosity, 300, the radius R, of the sphere that will obey Stokes law, is greater, but the final rate of motion of a sphere of 10 meters radius is nearly the same as in the case of the lower viscosity.

[1] R. A. Daly, *Igneous Rocks and Their Origin*, pp. 261–64.

action of crystallization as compared with the separation of the gases and liquids in deep-seated magmas. All magmas crystallize before they are found exposed as deep-seated types, for geological investigation. During the process of crystallization important changes in the aggregate density are likely to occur locally, and the quantitative importance of the change may be estimated. It will be assumed for the calculation that the early crystals are of average density. The specific-gravity increase when crystallization occurs will be 6 to 10 per cent. As outlined above, the viscosity is not enough to interfere with eruption if 40 per cent of the mass is crystalline. To make a conservative estimate—

Assume that 20 per cent of the mass is crystalline.

On the crystallization of one-fifth of the magma the specific gravity of the aggregate will rise from 2.70 to 2.73.

The density difference for any magma is at least .03.

The final rate of motion of a sphere of 10 meters radius is nearly 1,700 meters per hour.

The mineral composition of the early formed crystals may now be included in the calculation. If magnetite crystallizes, the change in specific gravity is estimated as .26 (see Table I); for olivine and augite the change in specific gravity is .19. These, when compared with the change in average gabbro used in calculation (.03), indicate that if the early minerals are magnetite and olivine or augite the specific-gravity difference should be greatly increased, though the change in density of the residual magma would of course be in the reverse direction. With other contributing factors the specific gravity may change as much as .06—twice as much as was assumed. The rate of motion might be even greater than would result from deep-seated vesiculation.

Combination effects.—It is known that two minerals may crystallize together, and that gas may separate from a magma during crystallization; even the separation of immiscible fractions during crystallization is a possibility. These combinations may retard or reinforce the general convection tendency due to simple thermal changes in density.

Use of the formula for flow of liquids through pipes.—If a cylindrical pipe of 10 meters radius be imagined as bent approximately

square, with sides as long as the depth of the magma chamber; and further, if the liquid in one vertical side of the square is kept more dense than the rest, circulation will occur. The formula for viscous or direct flow is[1]

$$Q=\frac{(p_1-p_2)\pi R^4}{8Lv},$$

where Q is the quantity passing a certain place in unit time, (p_1-p_2) the difference in pressure, R the radius of the tube, L the length of the tube, and v the viscosity of the liquid. With a constant radius of 10 meters and the added relation that the length of the tube is 4 times that of the column giving the pressure, the formula reduces to

$$Q=\frac{d_1-d_2}{V}\times\frac{1{,}000^2}{8\times4}\times\pi R^2=\frac{31{,}250\,\pi R^2(d_1-d_2)}{V},$$

where d_1 and d_2 are the specific gravities of the two upright columns.

The rate of flow can be derived from this by the quantity per second per unit cross-section:

$$x=31{,}250\frac{(d_1-d_2)}{V}$$

Comparison of estimates.—Tables II and III show the results in compact form.

TABLE II

ESTIMATED CONVECTION RATE, BY DIFFERENT METHODS, IN METERS PER HOUR

Viscosity (Water at .0115)	Phases	Settling Spheres	Flow in Pipe	Observed*
5	Hot and cool magma	1,000	2,200	....
5	Magma and gas bubbles	2,500	12,000	2,000–5,000
5	Magma and average crystals	1,700	6,600	....
5	Magma and heavy crystals	2,500	12,000	....
300	Hot and cool magma	1,000	40	....
300	Magma and gas bubbles	2,500	220	....
300	Magma and average crystals	1,700	113	....
300	Magma and heavy crystals	2,500	220	....

* R. A. Daly records the convection in a crater lake as 2 to 5 kilometers per hour in "The Nature of Volcanic Action," *Proc. Am. Acad. Arts and Sci.*, XLVII, 76.

The calculated results in other columns are not strictly comparable, as they are based on a pressure of 200 atmospheres, and the convection in the crater may be more active than that 3,000 feet below.

[1] Poynting and Thomson, *A Text-book of Physics* (1902), p. 209.

A recent paper by W. K. Lewis, in *Jour. of Ind. and Eng. Chem.*, VIII, 627–32, gives a good statement of the present methods of calculation. For small velocities the formula for viscous flow applies even to pipes of large diameter.

The relative slowness of motion of sinking crystals is evident from a comparison of the tables. In a sill 1,000 feet thick a large crystal of olivine might settle in a day or two, though it is not probable; small ones would require a few weeks. Convection might carry them down in half an hour, or much less if the viscosity was not at a maximum.

TABLE III

ESTIMATED RATE OF FALL OF SETTLING CRYSTALS OF 4 MM. DIAMETER IN METERS PER HOUR

Viscosity	Mineral	Rate of Motion	Viscosity	Mineral	Rate of Motion
5	Magnetite	132	300	Magnetite	2.+
5	Olivine	25	300	Olivine	0.5
5	Augite	25	300	Augite	0.5
5	Plagioclase (rising)	13	300	Plagioclase (rising)	0.2

THE PROCESS OF SOLIDIFICATION WITH CONVECTION

Form and size and composition of magma.—Small bodies of magma are usually cooled to crystallization too rapidly to permit much circulation. However, the actual limit in size is not to be stated, as the fluidity and duration of crystallization may in case of abundant mineralizers allow an effective convection in a four-foot dike. Thin, tabular masses are unfavorable to any general circulation after intrusion is complete, but no special form or position of the mass seems to prevent all circulation. If the mass is nearly horizontal, settling crystals are more effective than circulation. It has been suggested also that thick, strikingly dome-shaped laccoliths assume their form because of unusual viscosity.[1] In so far as this is so they would be unfavorable to convection. The viscosity of a magma during crystallization depends largely on its composition. Data are not abundant, but indicate that viscosity is greatly reduced by dissolved gases such as water vapor; also that medium to basic magmas are less viscous than acid magmas.

Rate of cooling.—Aside from its size, the temperature of the mass and of its walls affects the rate at which the magma passes

[1] Sydney Paige, "Progressive Increase of Viscosity during Intrusion," *Jour. Geol.*, XXI, 541.

the stage of crystallization. If the cooling is rapid no convection of importance occurs. If the borders are chilled, convection can be active only in the central portions. In considering convection effects then, we eliminate all suddenly chilled phases. There remain many igneous masses of large size in which the process of crystallization extends over a long period.[1]

Where cooling occurs.—At first intrusion cooling progresses from all sides, but, as shown in the discussion of the temperature gradient, later cooling would be largely from the top of the mass and related to surface radiation and ground-water circulation. However, in a mass of laccolithic or batholithic form enough cooling would occur at the sides to establish normally some circulation. Once the current is established it tends to develop in power, the cooling top layer being drawn over to the sides as the side layers sink.

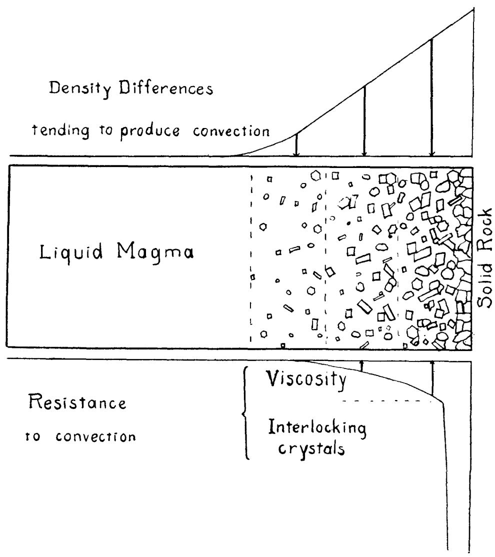

FIG. 1

The column of liquid which is effective in the motion is shown in Fig. 1, representing the zone of cooling near the side of the magma. The active force is much greater than the resisting viscosity up to the point where crystals begin to touch each other. It is greatest in a zone near the solidified wall. As crystallization progresses all the zones move inward. The width of these zones is wholly uncertain, but remembering the wide temperature range through which crystals may be in equilibrium with a magma, it seems probable that 20 meters (used in calculation) is a small estimate for large magma chambers.

[1] R. A. Daly, "Mechanics of Igneous Intrusion," *Am. Jour. Sci.*, XXVI (1908), 25.

The probable size of crystals in convection.—It is suggested[1] that if convection kept a supply of material at hand for the growth of a crystalline border, the largest crystals would be at the borders. This is actually the case in some pegmatitic differentiated dikes and indicates some movement in a thinly fluid magma. However, the mechanics of the process as outlined is not such as to furnish growing crystals a large supply of molecules from the central mother-liquor, though some such action may occur. The crystalline-border phase grows as a result of small crystals becoming caught in a more viscous, less rapidly moving wall. Here the progress of cooling is so advanced that, with the high viscosity, it is not to be expected that large crystals will develop.

The accumulation of crystals.—Most of the crystals, being heavier than the magma, would tend to settle; and though formed during the cooling along the top and sides of the chamber they would probably lodge at the sides and especially along the bottom during the forced circulation inward toward the rising current. Settling would here be entirely sufficient to remove crystals from the current. Similarly the crystals lighter than the magma would have a tendency to lodge along the roof and outer corners. Thus the segregation of minerals depends on gravity and is assisted by convection. It is largely independent of the place where cooling and crystal growth occur.

Orientation of crystals.—When a crystal once lodges in a viscous wall, too viscous to be again involved in general circulation, there may still be sufficient fluidity to allow orientation. The viscous matrix crystallizes, while the magma near it is still in motion, and the crystals would probably be oriented in the direction of the current—in most cases parallel to the walls of the chamber.

Gravity differentiation.—As most of the crystals of an igneous rock are heavier than the magma from which they grow, it will be expected that whichever forms first will segregate toward the bottom. It is only the coincidence of high gravity and early crystallization that results in a strict gravitative arrangement in the resulting rock. However, the general order of crystallization is, as a matter of fact, roughly the order of decreasing specific

[1] N. L. Bowen, "The Later Stages of the Evolution of Igneous Rocks," *Journal of Geology*, Supplement to Vol. XXIII (1915), p. 12.

gravity, and a gravitative arrangement is common. It is not to be expected that large segregations of a single mineral will be other than exceptional, because the cooling progresses in such a way that crystals of several minerals are likely to be growing at once and all settling together on the bottom as well as lodging along the walls. However, the conditions are easily conceived as possible for the formation of magnetite and peridotite near the base, and anorthosite near the top, of a single magma.

The behavior of immiscible liquids may be considered at this time. If the separation of globules occurred in a stationary magma, a gravitative rise and fall would tend slowly toward the separation of the fractions. If the immiscible liquids separate during convection, the smaller fraction, if light, will separate along the top, if heavy, along the bottom, as a fairly distinct layer in logical gravitative position. This layer may crystallize before or after the magma from which it separated, and the first to solidify may be intruded by the other. Abrupt gradations and contacts should be the rule. A small separated layer is likely to escape from the general circulation and is less likely to show a fluxion structure.

Double differentiation.—Thus it is conceived that a magma might differentiate into a series of bands dependent on the order of crystallization and settling, and *at the same time* give a rather abrupt gradation to a separated immiscible rock type—one of radically different composition. This is double differentiation. And the complexity of the sequence in some petrographic provinces is strong indication that two very different processes have been in operation.

Such a suggestion might apply to the occurrence of pyrrhotite at Sudbury which is said to have intrusive relations in some exposures to the main norite; and the norite itself is differentiated in roughly gravitative fashion.

Convection structures.—In discussing convection Pirsson makes the following suggestion: "Probably at first as the liquid moved inward over the floor of the laccolith and became reheated, these crystals [formed in the cooling border zones of the magma] would remelt, giving rise to numerous small spots of magma of a different composition, which would slowly diffuse."[1] It is noteworthy that

[1] L. V. Pirsson, "The Igneous Rocks of the Highwood Mountains," *U. S. Geol. Survey Bull. 237*, p. 188.

the result is, at least temporarily, a heterogeneous condition of the magma. Similar heterogeneity may result from crystals settling from an upper cooling zone into a deeper superheated zone. However, even more important variations in the magma are thought to result from the removal from the cooling zone of crystals of an early period of formation. Thus if a uniform magma had cooled on the outer edges of a laccolith until olivine crystallized, not only would there be convection due to the increased density of the olivine substance, but as the current moved along the floor some olivine crystals would settle out, leaving the liquid to rise in the central part of the mass with a different composition from the average.

It is important to consider in detail the result of this variation in the circulating magma. The material supplied by such a magma to the cooling border zone will differ from time to time and is almost certain to show some alternation because of a lack of rapid diffusion. As different material passed the cooling zone different crystals would be likely to develop, and a layer of different rock would be deposited on the walls and floor, giving rise to bands parallel to the current of magma and parallel to the walls of the chamber.

A further possible cause of alternation of materials deposited may be found in rhythmical activity of the cooling, or intrusion, or gas supply of the magma. Cooling is affected by annual and longer rhythms, but the depth of most of the igneous masses makes it unlikely that the rhythm from the surface would have notable effects. A rhythm in extrusive action is well recognized,[1] and the causes usually assigned to it would apply equally well to intrusive action. The supply of heat, gases, and lava may be distinctly periodic and may be responsible for the alternation of material crystallizing in the cooling zone of the magma.

Banding developed in this way is not likely to be perfectly regular, because of the irregularities of the current, its rise in the center, and its possible tendency to corrode or resorb some bands already deposited. Settling crystals on a large scale would tend

[1] J. D. Dana, *Volcanoes* (Dodd, Mead & Co., 1891), p. 124; Bonney, *Volcanoes*, pp. 274 ff.

to disturb the banding and give a gradation rather than an alternation in composition. It may be suggested also that stoped blocks settling in a magma would disturb such banding. Differentiation, however, is in no way interfered with[1] by the circulation that produces the banding.

SUMMARY

Several lines of evidence indicate that active convection occurred in many large, deep-seated magmas, and the process seems to be mechanically probable. In starting a current in such a mass the increase in density of growing crystals is probably more important than the development of any gas or separate liquid phases; and, added to the effect of simple cooling, the forces seem to be ample. Nearly all the field observations commonly made on igneous rocks may have a bearing on the question; probably first should be placed an alternation of bands of varying mineral composition; the position of the bands and the walls of the chamber; the mineral composition of the bands and the walls; any parallelism of grain and its direction; the form and size of the mass; grain variation near the margin; contact effects; the sequence of rocks formed in differentiation, continuous, double, or broken series; abrupt or gradual variations; intrusive relations between differentiates; gravitative or border position of differentiates; occurrence of one differentiate as a matrix for grains of another; the order of crystallization; signs of mineralizers, and their association with certain differentiates; globular forms.

The idea of convection becomes of practical service to the geologist when related to the banded structure. By it we may find the position of the walls of the chamber. The complexity of some differentiated rock series is best explained by assuming that some of the series developed during convection. Knowing the order of crystallization we can at once decide whether a mineral like magnetite is likely to be in bands near the bottom, or nearer the center, of the magma chamber. Finally a knowledge of the direction of the convection current aids greatly in estimating the extent of such a body of segregated magnetite.

[1] N. L. Bowen, "The Later Stages of the Evolution of Igneous Rocks," *Journal of Geology*, Supplement to Vol. XXIII (1915), p. 16, does not agree.